Preprint
UCRL-JC-148562

Small Nuclear Technology and Market Entry

Jeffrey S. Stewart, Robert N. Schock, Neil W. Brown, and Craig F. Smith

This article was submitted to
Institute of Nuclear Material Management 43rd Annual Meeting,
Orlando, Florida, June 23–27, 2002

June 2002

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

UCRL-JC-148562

Small Nuclear Technology and Market Entry*

Jeffrey S. Stewart,[1] Robert N. Schock,[2] Neil W. Brown,[3] and Craig F. Smith,[3]
Lawrence Livermore National Laboratory
University of California
Livermore, California, 94550

For Presentation to the Institute of Nuclear Materials Management
43^{rd} Annual Meeting
Orlando, Fl
June 25, 2002

Abstract

An overview of energy-system projections into the new century leads to the conclusion that nuclear power will play a significant role. How significant a role will be determined by the marketplace. Within the range of nuclear-power technologies available, small nuclear-power plants of innovative design appear to fit the needs of a number of developing nations and states. Under similar financing options used by the airline industry and others, the capital requirement barrier that puts the nuclear industry at a disadvantage in deregulated markets could be reduced. These plants have the potential advantage of modularity, are proliferation-resistant, incorporate passive safety features, minimize waste, and could be cost-competitive with fossil-fuel plants.

Introduction

As we enter the new millennium, the world is subject to forces that offer unique opportunities: the transition to a knowledge-based society, the emergence of a truly global economy, and the pursuit by society of sustainable systems with minimal environmental impact. These forces may converge to enable major improvements in the wealth-creating capacity and well-being of the world's inhabitants. Our own economy, society, political well-being, and even our security will benefit from these improvements. No single system is more important to this dynamic than energy, which powers the economy, provides the engine to increase the quality of life of all the globe's inhabitants, but at the same time is also the most responsible for environmental pollution of the atmosphere and oceans.

The Global Energy Future

What the energy systems of the future will be is unknown, but we do know that their mix and distribution will be determined by society's priorities as expressed in the

---

*This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

[1]Decision Sciences Group
[2]Center for Global Security Research
[3]Energy and Environment Program

marketplace. Current extrapolations and scenarios of global energy growth rates vary, but significantly, they center on 25 to 50% growth over the next 20 years and 250% growth over the next 50 years. It is interesting that a large number of recent scenarios done for the Intergovernmental Panel on Climate Change (IPCC) [1], as part of its most recent assessment of emission-mitigation strategies to stabilize carbon dioxide in the atmosphere, show even larger increases of up to 350% or three and one-half times existing energy-use levels. More importantly, the growth rates in electric power are even higher. A recent projection by the Electric Power Research Institute has a 500% increase in electric power by 2050 [2].

Where will all of this energy come from? Again we do not know, but the scenarios are instructive. **Figure 1** shows the results from modeling technology penetration, with projections of the range of their contributions to global electricity production in 2050 from 30 scenarios, chosen for different stabilization levels of carbon dioxide in the atmosphere and different economic assumptions. The median value of each technology over all scenarios is shown by a square.

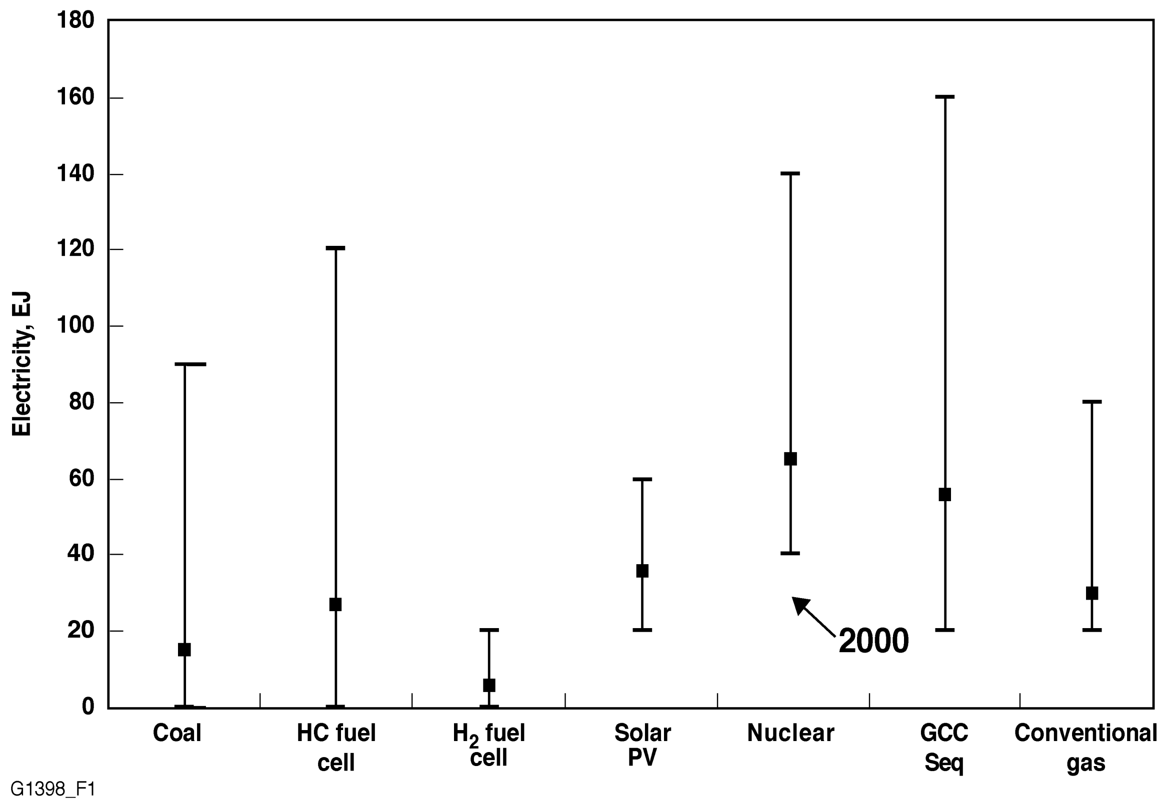

Figure 1. Ranges of electricity generation (EJ) across 30 scenarios for 2050. Each bar shows the range across different IPCC scenarios for a given technology from upper to lower bound. Squares indicate the median value. GCC Seq is natural gas combined cycle with carbon sequestration, HC is hydrocarbon, and H_2 is hydrogen. The arrow indicates current global nuclear electricity generation. [Data from References 1, 3, and 4].

Two important conclusions can be drawn from Figure 1. First, it will require a *range* of technologies to meet future global electrical power needs. Second, is that advanced nuclear power—assumed to cost more than today's nuclear electricity—is *on average* believed to be the largest single contributor to the world's energy mix in 2050. The preponderant contributor, even at the bottom of the range, averaged over all technologies, is nuclear energy.

What Kind of Nuclear Technology?

What type of nuclear energy might this be? Some insight comes from the fact that roughly two-thirds of the energy increases are projected to occur in the developing world [5]. A considerable part of this development by 2050 will almost certainly take place in East, Southeast, and South Asia, and in Latin America and the Middle East. There will, of course, be a need to replace existing plants and to support a level of growth in the developed world, but most of the overall growth can be expected in the developing world.

So we should ask, what type of power are the societies of these countries likely to want and can afford? Part of the answer comes from observing what is happening in the world to all types of systems. Miniaturization and modularization are becoming more and more prominent. Cellular telephones, personal digital assistants, aero-derivative gas-turbine power generators, fuel cells, and micro-turbine power units are all examples. This change is all part of a movement toward more efficiency, both energy and personal efficiency, driven by advances in micro- and nano-technology of materials. In electric power markets, decentralization and deregulation are having a similar impact. Small, efficient, modular power plants are being installed on a district scale, decreasing the need for regional or national electrical transmission grids, which in any case are becoming harder and harder to site. Fuel cells, which were big, cumbersome, and expensive a decade ago, are now one-tenth the size and 50% more efficient.

The International Atomic Energy Agency has determined that small- and medium-sized nuclear reactors could fill the needs of developing countries, from power generation, through district and process heat, to the production of potable water [6]. They estimate that, by 2015, developing countries are expected to require almost 100 small- and medium-sized reactors, typically thought to center on the range of 100 to 200 megawatt-electric (MWe), and may be as small as 50 MWe and as large as 300 MWe. South Korea, China, Argentina, and Japan, among others, are developing reactors to fill this projected need. Not all of the new reactors to be added over the next 50 years will be small ones, but a significant number may be. Can they compete in the marketplace? The answer lies in more than just cost—it also will be determined by convenience and reliability. People are willing and able to pay much more for cellular telephone service because of its convenience. Some people are willing to pay more for bottles of clean water than they pay for the same volume of gasoline.

Features of Small, Innovative Reactors

The report on the Geopolitics of Energy [7], released by the Center for Strategic and

International Studies and chaired by former Senator Nunn and former Department of Energy Secretary Schlesinger, listed three essential conditions for nuclear-power reactors to be suitable for developing countries: they must be modular with a generating capacity of about 100 MWe, they must be cost-competitive with fossil-fuel power plants, and they must be proliferation-resistant. We would explicitly add inherently safe to this list.

Small nuclear-reactor technologies generally fit the criterion of modularity. The nuclear-reactor system should ideally be delivered to the site already assembled and not require refueling during its lifetime. This also means the reactor is already fueled when shipped to the site. Elimination of on-site refueling and fuel access reduces proliferation concerns. This attribute can only be incorporated into a small reactor and should reduce the cost and complexity of the system.

For cost-competitiveness, it is helpful to look at the recent electrical generation marketplace. A modern coal-fired power plant costs $1.50 per watt to build and 1¢ to 1.5¢ per kilowatt-hour (kWh) to operate. A small gas-fired, aero-derivative turbine plant costs 60¢ per watt to build and 3.8¢ per kWh to operate. A large modern nuclear plant costs between $1.50 to $2.00 per watt to build and around 1¢ per kWh to operate. This is the arena in which small nuclear plants have to compete. The commercial designers of at least one small system, the Pebble Bed Modular Reactor (PBMR), claim that a 110-MWe module can be built and operated more cheaply than these options [8]. Only time and experience will verify their claim. The PBMR is just one system that needs to be examined in more detail.

In general, the capital costs of small reactors should be reduced because of minimal containment size, simpler reactor control and refueling systems, and modular construction and factory fabrication. Operating costs should be lower because of higher fuel burnup leading to reduced fuel costs and smaller volumes of waste, fewer refueling shutdowns, increased automation and consequent reduction in staffing, and simpler decommissioning. Significant cost savings would be associated with reductions in the number of highly trained staff at the site. However, unknown added expenses may be expected in shipping a fully fueled reactor and installing it at the site. The interest cost on fuel for a full lifetime is a challenge that must be overcome.

Small reactors lend themselves to incorporating safety features that reduce reliance on expensive active safety systems. Credible failures should be safely terminated by inherent mechanisms in the nuclear system without releasing radioactivity. Postulated severe accidents should be terminated without requiring emergency off-site responses. An approach to recover from such situations that permits recovery of the site should also be identified. This capability is a necessary corollary to achieving the staff reductions envisioned above.

It is desirable to have replacement and disposal integrated into a system's design. One of the features inherent in the concept of no on-site refueling is that at the end of its core life, the entire reactor module is replaced. Innovative design incorporating the replacement, reconditioning, and disposal of expended reactor modules—including the disposition of spent fuel—is an important goal.

These are especially demanding goals likely achievable only with systems of relatively low power compared with large plants typical of modern construction. However, satisfying these goals has the potential to increase the security, safety, and public acceptance of the expanded use of nuclear power—one vision for small, innovative reactors.

One of the major challenges is to accomplish these goals with an economically viable system. Previous approaches to nuclear-power economics relied on "economies of scale"—the larger, the cheaper per unit of power. For small reactors, economics must be approached from a different perspective: they must rely instead on the economics of mass production, coupled with cost savings achieved from factors including substantially reduced on-site installation, operation and decommissioning costs; reduced site infrastructure requirements; and substantial improvements to streamline the licensing process.

Large nuclear-power systems require complex emergency systems for heat removal and control, complex monitoring and control systems, extensive infrastructure for construction, operation, and maintenance, and a large electric grid to transport the generated electrical power. Small reactors, on the other hand, can be designed for unattended, high-reliability operation, factory manufacture and assembly is greatly facilitated, and the complexity of reactor safety systems can be simplified. Several associated benefits are enabled by small reactor size:

- As a result of simplified operations and reliance on autonomous control and remote monitoring, operating costs are lower.

- Development of new, small systems enables a comprehensive systems approach to nuclear-energy supply and infrastructure design, with all aspects of equipment life, fuel, and waste cycles included.

- Transport by barge or ship enables factory manufacturing and reduced infrastructure requirements.

- No refueling or a replaceable core within a standardized modular design results in minimized fuel handling and enhances non-proliferation assurance.

- Large safety margins, high reliability, and reduced maintenance are enabled by resilient and robust designs.

- Waste minimization and waste-form optimization can be built into the fuel cycle from the beginning.

Small Reactor Types

Table 1 lists some of the key parameters associated with various small innovative reactor concepts. Small reactors, like large ones, can be broken into several categories. One way to characterize them is by the type of cooling fluid. Several types use water and are described as small advanced light-water-cooled reactors (LWRs). These types stress enhanced safety, simplicity through fewer components, modular manufacturing, output in the range of 100 MWe, high fuel burnup thus reducing the amount of waste and enhancing the recycle time, and higher efficiency than current or planned LWRs, although not all types incorporate every feature. The core can sometimes be removed together with the vessel and the changeover done outside the host country. The Westinghouse IRIS system (International Reactor Innovative and Secure) is an example. South Korea is designing a small reactor mounted on a barge called SMART (Small Modular Advanced Reactor Technology).

Another technology much discussed today is the modular gas-cooled reactor using helium as the coolant and using a high-temperature gas turbine to generate power. One version of this concept uses fuel incorporated into graphite spheres the size of billiard balls that contain coated fuel particles capable of very high burnup and high retention of fission products. Another type of gas-cooled, graphite-moderated reactor, the Modular High-Temperature Gas Reactor (MHTGR), uses fuel elements in the shape of hexagonal graphite blocks and are periodically refueled off-line.

Table 1. Summary of Small Innovative Reactor Characteristics.

Characteristic	Light-Water-Cooled		Gas-Cooled		Liquid-Metal-Cooled			Other Concepts	
Concept	Westinghouse IRIS[a]	So. Korea SMART[b]	Eskom PBMR[c]	GA/Russian MHTGR[d]	Japan 4S [e]	UC Berkeley ENHS[f]	Argonne Star-LM[g]	Molten-Salt[h]	Heavy Water[i]
Development Status	Pre-conceptual design	Conceptual design	Conceptual design	Conceptual design	Conceptual Design	Pre-conceptual design	Pre-conceptual design	No design activity	No design activity
Power (MWth/MWe)	300/100	330/90	230/100	600/280	125/50	125/50	300/100	350/155	?/100
Inlet temp, °C	292	270	490	490	430	430	292	550	280
Outlet temp, °C	330	310	800	850	550	550	550	700	320
Operating pressure, MPa	15	15	7.0	7.1	0.1	0.1	0.1	0.1	15
Fuel	UO_2 or MOX	UO_2 or MOX	UO_2 or MOX graphite pebbles	UO_2 or MOX graphite blocks	U and U/Pu metal	U and U/Pu metal	U metal	U fluoride salts	UO_2 or MOX
Refueling, Yr	7	2	On-line	2	30	>15	15	On-line	On-line
Power conversion	Steam turbine	Steam turbine	He gas turbine	He gas turbine	Steam Turbine	Steam turbine	Steam turbine	Gas turbine	Steam turbine
Reactor vessel size, m	18 x 4.4	9.8 x 3.9	25 x 9	25 x 7.3	23 x 2.5	19 x 3.2	14 x 5	8 x 12	Pressure tube

[a] Mario Carelli, et al., "IRIS Reactor Development," *9th International Conference on Nuclear Engineering*, April 8–12, 2001, Nice, France.

[b] Ju-Hyeon Yoon, et al., "Design Features of SMART for Barge-Mounted Application," *Propulsion Reactor Technology for Civilian Applications*, IAEA Advisory Group Meeting, Obninsk, Russia, 20–24 July 1998, IAEA-AG-1021.

[c] www.pbmr.co.za/2_about_the_pbmr/2_about.htm

[d] Utility/User Incentives, *Policies and Requirements for the Gas Turbine Modular Helium Reactor*, General Atomics, September 1995, DOE-GT-MHR-100248.

[e] Y. Nishiguchi, et al., "Super-Safe, Small, and Simple Reactor Concept Toward the 21st Century," *Proceedings of the Workshop on Proliferation-Resistant Nuclear Power Systems,* Center for Global Security Research, Lawrence Livermore National Laboratory, June 1999.

[f] E. Greenspan, D. Saphier, D.C. Wade, J. Sienicki, M.D. Carelli, L. Conway, M. Dzodzo, N.W. Brown, and Q. Hossain, "Promising Design Options for the Encapsulated Nuclear Heat Source Reactor," submitted to ICONE-9 (2001).

[g] B.W. Spencer, et al., "An Advanced Modular HLMC Reactor Featuring Economy, Safety, and Proliferation Resistance," *8th International Conference on Nuclear Engineering*, Baltimore, Maryland, April 2–6, 2000.

[h] K. Furukawa, et al.," Small Molten-salt Reactors with a Rational Thorium Fuel Cycle," *IAEA Second International Seminar on Small and Medium Sized Reactors*, San Diego, California, August 21–23 1989.

[i] R.S. Hart, "The CANDU 80," *Proceedings of an IAEA Advisory Group Meeting on the Introduction of Small and Medium Reactors in Developing Countries*, Atomic Energy of Canada Ltd., Canada, IAEA-TECDOC-999, February 1998.

A third type of small reactor uses liquid metal as the coolant. The low vapor pressure of the metal coolant permits thin-walled reactor vessels that make the factory-assembled system lighter in weight and more easily transported. These reactors are not moderated and operate with a neutron energy spectrum much higher than reactors moderated with water or graphite and cooled with water or gas. This supports high internal conversion of fertile to fissile materials and the potential for a very long core life. The liquid metal coolant with the most experience is sodium, but lead–bismuth alloys have also been used, and lead is being considered by the Russians [see for example Reference 9].

One version of this type is the conceptual design for the Encapsulated Nuclear Heat Source (ENHS)**.** The ENHS is a liquid metal-cooled reactor (LMR) that uses either lead (Pb) or a lead-bismuth (Pb–Bi) alloy as the reactor coolant. The ENHS concept is characterized by a large thermal inertia because of the large inventory of the primary and secondary liquid-metal coolant, making the concept inherently safe. In all accident sequences, heat can be transferred to the vessel boundary by conduction and natural convection while the fuel and cladding temperatures remain significantly below safety limits.

Other concepts are in various stages of development. Molten salt has been considered both as a coolant and as a fuel. Cooling with heavy water is also being considered and the heavy water serves as both as a moderator and as a coolant.

Life Cycle Cost

We recently competed a study on the life cycle cost of mass-producing the ENHS reactor (Reference 13). The study was based on the actual conceptual design proposed, developing the engineering, manufacturing, transportation dismantlement and disposal infrastructure required for a life-cycle study. The major assumptions used in the base case include—

- Annual Number of Units Produced—50
- Interest Rate During Construction—8%
- Construction and Testing time—30 months
- Separative Work Units (SWUs) cost—$85
- U_3O_8 cost—$30/kg
- Capacity Factor—90%

Seven sensitivity cost studies were analyzed:

(1) A doubling of site labor cost;
(2) A doubling of factory labor cost;
(3) High SWU cost—$100;
(4) High U_3O_8 cost—$50/kg;
(5) A high interest rate—10%;
(6) A lower capacity factor—80%; and
(7) A longer construction period—8 years plus 6 months of testing.

In the base case, the overall cost of electricity is estimated at 3¢/kWh, or, $30/MWh. **Figure 2** shows that nuclear fuel is the largest single cost component for the unit. The cases that vary the costs of enrichment and the cost of U_3O_8 over plausible ranges show that these factors could increase the cost of electricity by up to 10%. The most expensive case is Longer Construction Time. This raises the cost by about 21%.

The costs of site labor and factory labor have been roughly estimated in this analysis. However, the cost of factory labor has relatively little impact on the overall cost because it accounts for a small fraction of the total cost. Site labor could have a significant effect on the cost because it accounts for nearly 30% of the total annual cost. Doubling the site labor costs increases the total cost by about 20% (**Table 2**).

Figure 2. Breakdown of annualized costs by cost category for Base Case.

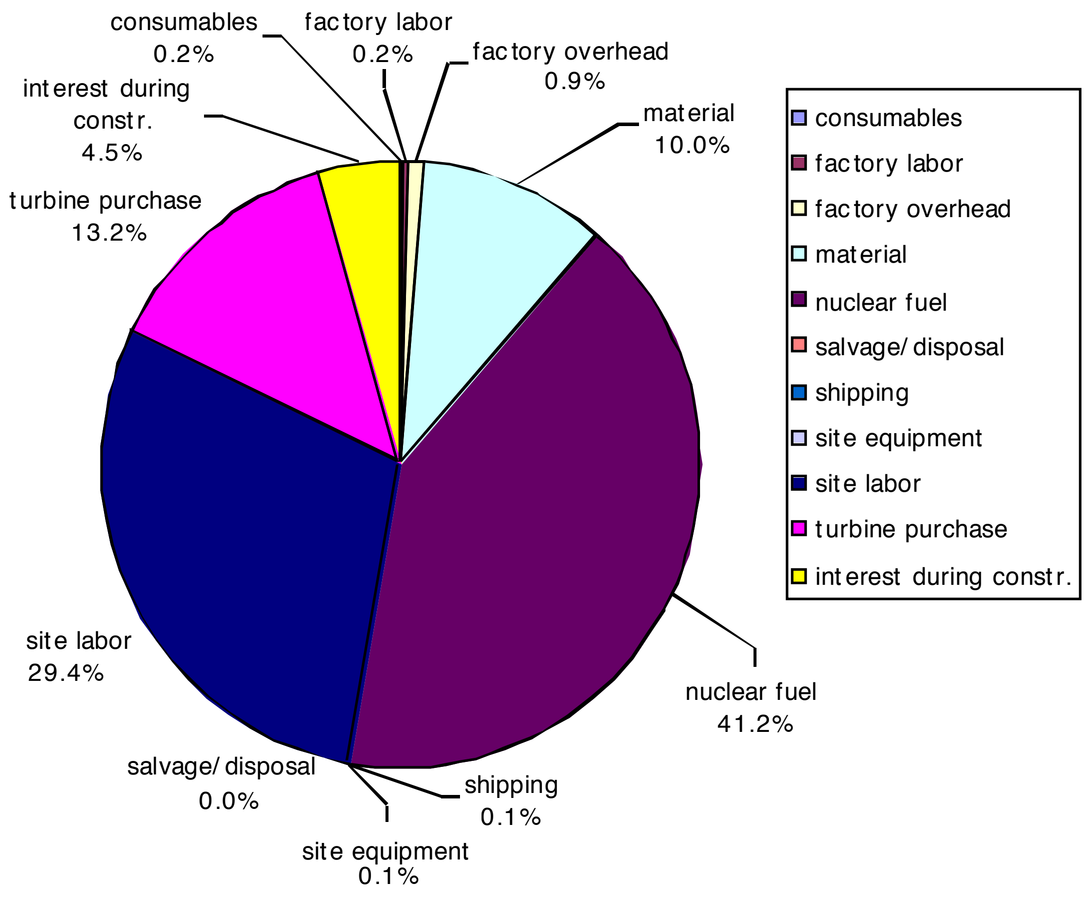

Table 2. Summary of capital costs and cost of electricity for cases analyzed.

	Base Case	Site Labor 2X	Factory Labor 2X	High SWU Price	High U_3O_8 Price	High Interest Rate	Lower Capacity Factor	Longer Constr Period
Total unit capital cost, $/kWe	2,000	2,012	2,007	2,130	2,233	2,044	2,000	2,610
O&M costs, $M/yr	2.19	4.35	2.19	2.19	2.19	2.19	2.19	2.19
Busbar costs, ¢/kWh								
Capital	1.00	1.02	1.01	1.01	1.02	1.27	1.13	1.63
O&M	0.56	1.10	0.56	0.56	0.56	0.56	0.63	0.56
Fuel	1.40	1.40	1.40	1.56	1.68	1.62	1.58	1.40
Total	2.96	3.52	2.97	3.13	3.26	3.45	3.33	3.59

Note: Includes the "end of life costs" (removal, dismantlement, etc) for components.

Approaches for Financing Small Modular Reactors (SMR)

To increase the customer base, businesses and financial institutions have created numerous ways to ease the financing of products. The modularity of the ENHS and other small nuclear reactors conceptually allow for long-term leasing arrangements. The airline industry increased the market for airplanes with the creation of leasing companies [10]. These companies have allowed new passenger and freight carriers to enter the market in an industry that normally requires large capital expenditures. The increase in low-fare and small regional carriers is in part due to the ability to lease planes at a fraction of the startup cost of purchasing a fleet. By needing less capital to enter or expand in the airline market, more companies have been able to enter, and more planes ultimately sold. **Tables 3** and **4** illustrate the cost to lease the ENHS using terms similar to the airline industry.

The four cases selected show the largest cost impediments to deploying SMR.

Table 3. Leasing Scenario for each option at 8% annual interest.

	Base Case	High SWU Enrichment ($100/SWU)	High U_3O_8 Price ($50/kg)	Longer Construction Period
Plant Cost ($K)	100,071	106,555	111,683	100,023
Capacity Factor	0.9	0.9	0.9	0.9
Lease Term (Year)	30	30	30	30
Deposit ($K)	(17,778)	(18,930)	(19,841)	(17,770)
Monthly Cost ($K)	(741)	(789)	(827)	(740)
Cost of Electricity (¢/kWh)	(2.30)	(2.43)	(2.55)	(2.2)

Table 4. Leasing Scenario for each option at 10% interest.

	Base Case	High SWU Enrichment ($100/SWU)	High U_3O_8 Price ($50/kg)	Longer Construction Period
Plant Cost ($K)	100,071	106,555	111,683	100,023
Capacity Factor	0.9	0.9	0.9	0.9
Lease Term (Year)	30	30	30	30
Deposit ($)	(21,231)	(22,606)	(23,695)	(21,221)
Monthly Cost ($K)	(885)	(942)	(987)	(884)
Cost of Electricity (¢/kWh)	(2.73)	(2.91)	(3.1)	(2.73)

A SMR owner could decide to reduce the traditional operational and maintenance staff by leasing some of the maintenance services. Major components such as turbines and steam-generator maintenance contracts could be set up as part of the leasing agreement, freeing the utility from maintaining a staff for routine procedures. This could also be done more efficiently by the manufacturers who would be contracted to repair potentially hundreds to thousands of these identical parts.

The success of this type of arrangement is contingent on a market for used nuclear power reactors and components.

Other Applications

In addition to the generation of power, SMRs also have other important potential applications, which may or may not be coincidental with the generation of electricity. These applications include the desalination of seawater, the decontamination of polluted water, the use of the heat for co-generation of electricity or district heating or for industrial process heat, and the generation of hydrogen by electrolysis during off-peak periods for subsequent regeneration in fuels cells either for grid power or to power vehicles. These applications have not been examined for their potential impact on life-cycle cost.

Acknowledgments

Part of this paper is drawn from a presentation at the James A. Baker III Institute, Rice University, Houston, Texas, in March of 2001.

References

1. N.J. Nakicenovic, G. Alcamo, B. Davis, J. Fenhann de Vries, et al., *Special Report on Emissions Scenarios*, A Special Report of Working Group III of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, U.K., 2000).

2. *Electricity Technology Roadmap*, Electric Power Research Institute, Palo Alto, California, 1999.

3. N. Nakicenovic and K. Riahi, *An Assessment of Technological Change Across Selected Energy Scenarios,* Report to the World Energy Council (London), to be published, 2001.

4. *BP Amoco Statistical Review of World Energy*, BP Amoco, London. Web site address: www.bpamoco.com/worldenergy.

5. *Energy for Tomorrow's World,* World Energy Council, London (St. Martins Press, New York, 1993.)

6. "Introduction of Small and Medium Reactors in Developing Countries," *Proceedings of IAEA Advisory Group Meetings*, 23–27 Oct 1995 in Rabat, Morocco and 3–6 Sept 1996 in Tunis, Tunisia, International Atomic Energy Agency, Vienna.

7. *The Geopolitics of Energy in the 21st Century,* Center for Strategic and International Studies, Washington DC, 2001. Web site address: www.csis.org/sci/geopoliticsexecsum.pdf.

8. M. Popper, "A Second Chance for Nukes in America?" in *Streetwise, BusinessWeek Online*, February 20, 2001.

9. *White Book of Nuclear Power*, E.O. Adomov, ed., Research and Development Institute of Power Engineering (NIKIET), Moscow, 1998.

10. J.S. Stewart, A.D. Lamont, G.F. Rothwell, and C. Smith, *An Economic Analysis of Generation-IV Small Modular Reactors,* Lawrence Livermore National Laboratory, Livermore, California, UCRL-ID-148437 (March 2002).

University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551